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Precise Photometry and Spectroscopy of Transits

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Abstract. A planetary transit produces both a photometric signal and a spectroscopic signal. Precise observations of the transit light curve reveal the planetary radius and allow a search for timing anomalies caused by satellites or additional planets. Precise measurements of the stellar Doppler shift throughout a transit (the Rossiter-McLaughlin effect) place a lower bound on the stellar obliquity, which may be indicative of the planet's migration history. I review recent results of the Transit Light Curve project, and of a parallel effort to measure the Rossiter effect for many of the known transiting planets.

1. Introduction

I have great admiration for the people who discover transiting planets. Identifying the candidate transit signals from among a hundred thousand light curves, and flushing out the numerous astrophysical false positives, are impressive feats. This article, however, is not about transit discovery, but rather about the next step: performing high-precision photometry and spectroscopy of exoplanetary transits. The goal of this step is to determine the planetary and stellar properties well enough to allow for meaningful comparisons with the familiar properties of the Solar system, and to inform our theories of planet formation.

The most immediate result of transit photometry is a measurement of the planetary radius. In combination with the planetary mass, which can be inferred from the Doppler orbit of the star, these data give the first clues about the composition, interior structure, and atmospheric energy balance of the planet. An accurate radius is also needed to interpret the results of other observations, such as the detection of thermal emission or reflected light based on secondary-transit photometry. The timings of the transits can be used to refine the measurement of the orbital period and search for additional bodies in the system. In § 2, I describe the Transit Light Curve (TLC) project, an effort to gather high-precision photometry during exoplanetary transits.

The most prominent spectroscopic signal during a transit is the Rossiter-McLaughlin (RM) effect. This effect is an anomalous Doppler shift that arises from stellar rotation. Measuring this effect allows one to assess the alignment between the planetary orbital axis and the stellar spin axis, a fundamental system property that provides clues about the process of planet migration. I describe some recent measurements of the RM effect in § 3.

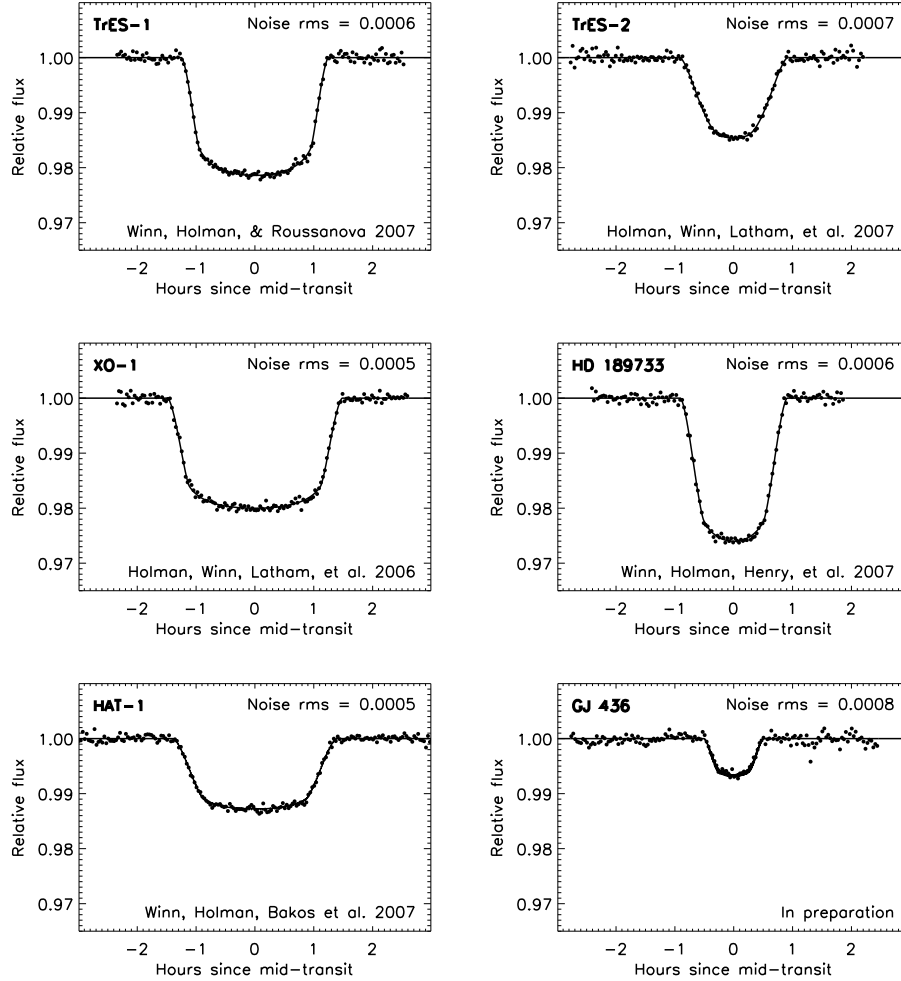


Figure 1. **The Transit Light Curve project.** Each panel shows time-binned photometry from a campaign (2-5 separate transits) for a particular planet. Most of the data are z band observations with the FLWO 1.2m telescope and KeplerCam detector.

2. The Transit Light Curve project

The most spectacular transit light curves have come from space-based observations with the *Hubble Space Telescope* (Brown et al. 2001, Pont et al. 2007) and the *Spitzer Space Telescope* (Knutson et al. 2007). However, it is important to remember that the extreme precision with which the relative flux can be recorded ($\sim 10^4$ per 30 s sample) does not guarantee an extremely precise value for the planetary radius. Rather, the transit depth $\Delta F \approx (R_p/R_\star)^2$ is known precisely, but R_p is known only as well as R_\star . The stellar radius must be estimated using other observable properties of the star, such as its parallax, luminosity, angular diameter, or spectrum.

Actually the situation is slightly more complex. In addition to the transit depth, precise photometry provides a few other observables, among which are the photometric period P , the total transit duration t_T (from first to fourth contact), and the full transit duration t_F (from second to third contact). Kepler’s third law can be used to write an accurate expression for the mean stellar density in terms of observable quantities (Seager & Mallen-Ornelas 2003):

$$\rho_\star = \frac{32}{G\pi} P \frac{\Delta F^{3/4}}{(t_T^2 - t_F^2)^{3/2}} \quad (1)$$

This approximation assumes $M_p \ll M_\star$, $R_p \ll R_\star \ll a$, and a circular orbit, but it is straightforward to generalize this expression. Thus, precise photometry reveals the mean stellar density.

This is helpful because it means that the light curve itself helps to estimate the stellar radius. A traditional method for estimating the stellar radius is to compare the spectroscopic values of T_{eff} , $\log g$, and metallicity with the output of theoretical models of stellar evolution. With excellent transit photometry it is advantageous to use ρ_\star instead of $\log g$ (see, e.g., Sozzetti et al. 2007, Holman et al. 2007). A related point is that in some regions of the HR diagram, the stellar *mass* is constrained at least as well as the stellar radius. At fixed stellar density—that is, with a perfect transit light curve—the error in R_\star (and hence R_p) varies only as the cube root of M_\star . In such cases the systematic error in R_p would be reduced by a factor of three relative to a situation in which only the transit depth (and not the durations) were known.

Another quantity that can be written purely in terms of observables is the planetary surface gravity (Southworth et al. 2007). In this sense, what a transit observer *really* measures is the stellar mean density and the planetary surface gravity. Transforming these variables into R_p and M_p requires external information.

In 2006, Matt Holman and I wondered whether it would be possible to reach the limiting precision in R_p by combining the results of repeated ground-based observations. We began the Transit Light Curve (TLC) project, with the aim of building a library of transit photometry of uniformly high quality, along with unified and rigorous methods for parameter determination. Our workhorse is the Fred L. Whipple 1.2m telescope and KeplerCam detector. We have also used the 6.5m Magellan telescopes for the OGLE systems, which are both southerly and faint. We have found that by employing these instruments and some straightforward observing protocols, it is possible in some cases to reach the limit in which the error in R_p is dominated by the uncertainties in the stellar properties rather than the photometric uncertainties.

Among our observing protocols are the following. When possible we center the field in such a way as to encompass at least 5 comparison stars of similar brightness to the target star. We keep the image registration as consistent as possible throughout the night. We defocus, if needed, to broaden the point-spread function to a consistent width of 5-7 pixels; this often has the salutary effect of enhancing the duty cycle by lengthening the maximum exposure time. We ensure that the flat-field calibration frame has enough counts to correct for $\sim 0.1\%$ pixel-to-pixel sensitivity variations. We observe not only the entire transit but also at least 1 hr prior to ingress and 1 hr after egress. We use the

reddest available optical bandpass (often Sloan z), for two reasons: to minimize the effect of differential extinction on the relative photometry, and to minimize the effect of limb darkening on the transit light curve.

Figure 1 is a gallery of some of our composite light curves, along with the standard deviation of the noise and citations to published results. Figure 2 shows the favorable noise characteristics that we have found for a subset of our target systems. Naturally, the best results are obtained when the field of view offers numerous good comparison stars and when the sky conditions are pristine. (Even relative photometry benefits from “photometric” nights.) A photometric precision of 0.15% with 30-second sampling is typical.

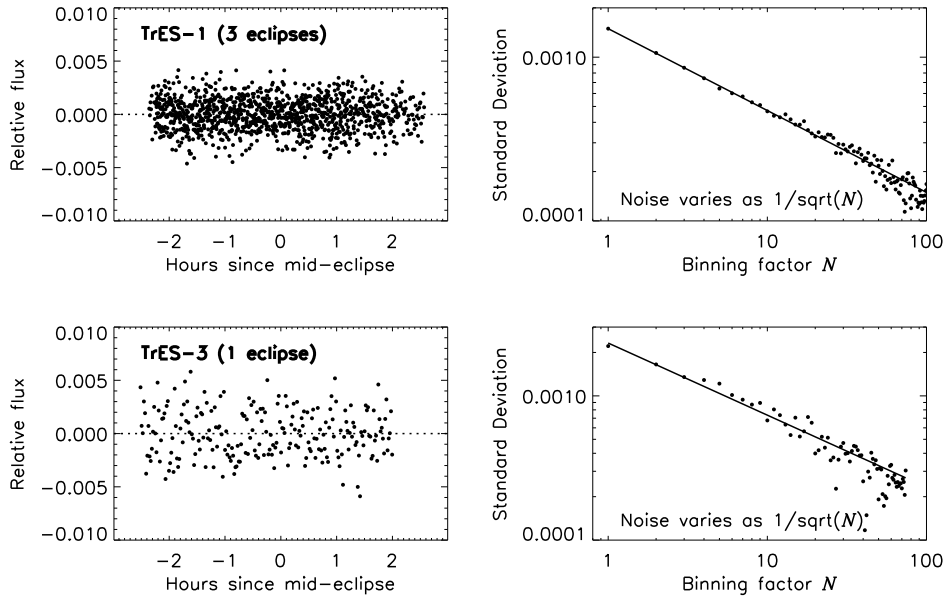


Figure 2. Photometry of TrES-1 and TrES-3, after subtracting the best-fitting model. The left panels show the residuals as a function of time. The right panels show the standard deviation of the binned residuals, as a function of the bin size. For these systems the noise varies as $N^{-1/2}$ as one would expect for uncorrelated Gaussian noise. The data sets exhibiting these favorable characteristics generally come from observations on photometric nights of systems for which 5 or more good comparison stars are available.

We have written a comprehensive analysis code that simultaneously fits multiple transits observed in different bandpasses, secondary transits (when such data are available), and radial velocities (including the Rossiter-McLaughlin effect; see § 3). We use a Markov Chain Monte Carlo algorithm to estimate the joint *a posteriori* probability distribution for all relevant parameters. Going forward, we intend to make some potentially important improvements to the code, including a more sophisticated treatment of “red noise” employing a model of the covariance matrix (at the moment we use a crude approximation), and a principal-component decomposition of the limb darkening function.

Over the longer term, we hope to detect (or rule out) additional planets and satellites of the transiting planet. These may manifest themselves through gradual changes in the transit duration caused by orbital precession (Miralda-Escudé 2002, Heyl & Gladman 2007) and by short-term variations in the mid-transit times due to multi-Keplerian motions or mutual gravitational interactions. We are gathering a large number of transit times with a precision of 0.25-1 min. Holman & Murray (2005) and Agol et al. (2005) have shown that transit-timing variations of that order could be produced by perturbers as small as the Earth, as long as they are in mean-motion resonances with the transiting planet. Resonances might be a common outcome of planet formation and migration, and searching for transit-timing variations is one way to find out.

3. The Rossiter-McLaughlin Effect

A striking pattern in the Solar system is its coplanarity. The orbital axes of the 8 planets line up to within a few degrees, and the Sun’s spin axis differs by only 7 degrees from the Earth’s orbital axis. The observed coplanarity was the original inspiration for the theory that the Sun and planets condensed from a single spinning disk. It would be interesting to know whether this degree of alignment is typical of all planetary systems. Exoplanets have provided enough surprises that nothing should be taken for granted.

Indeed there are reasons to expect at least occasional misalignments. Among the surprises to which I just alluded is that planetary orbital eccentricities are often large; whatever mechanism perturbs orbital eccentricities may also perturb inclinations. For close-in planets, which are thought to have formed at large orbital distances and then migrated inward, one may wonder whether the migration process disturbed the original alignment. The various migration theories differ on this point. Migration via tidal interactions with the protoplanetary disk should not perturb the alignment and may even drive the system toward closer alignment (Ward & Hahn 2003). In contrast, migration via planet-planet scattering would magnify any initial misalignments (Chatterjee, Ford & Rasio 2007), and migration via Kozai cycles accompanied by tidal circularization results in a broad distribution of final inclination angles (Fabrycky & Tremaine 2007). Thus, measuring the alignment between the orbital axis and the stellar spin axis is a means for testing migration theories and for identifying planets that migrated in interesting ways.

Transit observations can be used to assess the spin-orbit alignment, courtesy of a spectroscopic effect observed long ago by Rossiter (1924) and McLaughlin (1924) in eclipsing binaries. During a transit, the planet hides part of the rotating stellar disk, causing an “anomalous” Doppler shift. When the planet transits the approaching (blueshifted) half of the star, the net starlight appears slightly redshifted, and vice versa, as shown in Fig. 3. For the configuration shown, in which the transit impact parameter is approximately 0.5, the signal for a well-aligned planet is antisymmetric about the midtransit time, whereas a strongly misaligned planet that spends all its time covering the receding half of the star would produce only an anomalous blueshift. The key parameter is λ , the angle between the sky projections of the orbital axis and the stellar rotation axis.

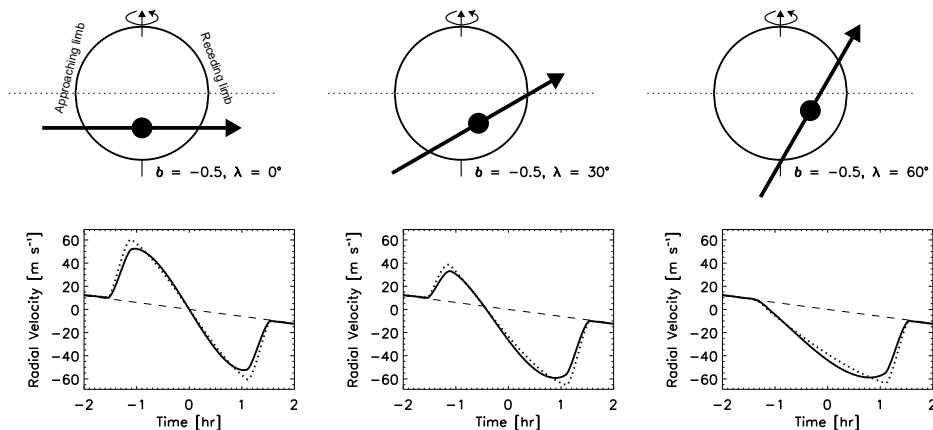


Figure 3. **The Rossiter-McLaughlin effect.** Shown are three planet trajectories that produce identical light curves, but have different orientations relative to the stellar spin axis and hence produce different Rossiter-McLaughlin signals. In the bottom panels, the dotted lines show a model of the effect in the absence of limb darkening; the solid lines show a model that includes limb darkening. Adapted from Gaudi & Winn (2007).

Measurements of the projected spin-orbit angle λ have been published for 5 systems (Queloz et al. 2000, Winn et al. 2005, 2006, 2007; Wolf et al. 2007; Narita et al. 2007). In all cases λ is consistent with zero at the $1\text{--}2\sigma$ level, with accuracies ranging from $1\text{--}30$ degrees. This has led to the working hypothesis that the migration of hot Jupiters generally preserves spin-orbit alignment. Importantly, star-planet tidal interactions (which are responsible for spin synchronization and orbital circularization of the planet) do not confound the interpretation because the expected timescale for tidal reorientation is generally 10^{10} yr or longer, as estimated using the equilibrium-tide theory of Hut (1981).

Observations of the Rossiter-McLaughlin effect provide only a lower limit on the stellar obliquity, the angle between the orbital and rotation axes. The RM waveform is sensitive to the angle between the sky projections of those axes, and the inclinations with respect to the sky must be determined with other data. The orbital inclination is often known to within ≈ 1 deg from the transit light curve, but the stellar inclination is usually unknown. The single exception thus far is HD 189733. That star is chromospherically active and exhibits quasiperiodic flux variations (presumably due to star spots) from which the rotation period can be measured (Henry & Winn 2007). The combination of a measured rotation period, stellar radius, and projected rotation rate (which can be measured from either the amplitude of the RM effect or from the observed spectral-line broadening) places a constraint on the stellar inclination, which is consistent with being edge-on.

More work remains to be done on confronting the specific predictions of planet-planet scattering and Kozai cycles with the data. The case of HD 147506 (also known as HAT-P-2) is especially interesting because the planet has a highly eccentric orbit ($e = 0.5$), naturally raising the possibility of planet-planet scat-

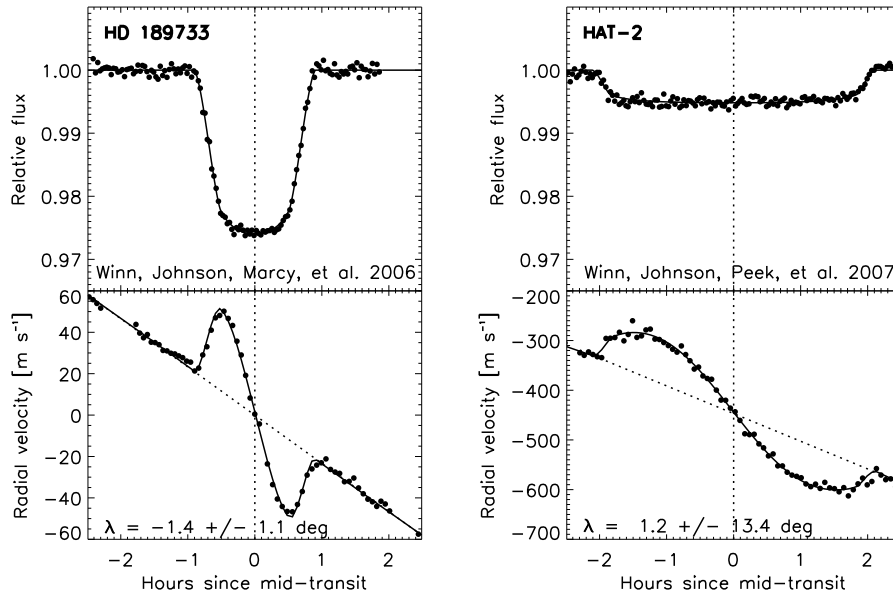


Figure 4. Photometric and spectroscopic observations of transits of HD 189733 (left) and HD 147506 (right; also known as HAT-P-2). The radial velocity data during the transit exhibit the Rossiter-McLaughlin effect. The projected spin-orbit angle λ was found to be small in both cases, through a simultaneous fit to the photometry and radial-velocity data. The precision is much lower for HD 147506 because the transit is nearly equatorial, which causes a strong degeneracy between $v \sin i$ and λ (see Gaudi & Winn 2007).

tering or Kozai cycles, yet the system is well-aligned (Winn et al. 2007). In this case, however, the achievable accuracy in λ was limited to about 14 degrees because the transit is nearly equatorial. In such cases the Rossiter waveform is always antisymmetric and the value of λ is encoded in the *amplitude* of the signal, which causes a strong degeneracy with the value of the stellar projected rotation velocity (see Gaudi & Winn 2007).

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